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Excitation Functions for the Deuteron Induced Reactions on ^{64}Zn and ^{76}Ge

Tomota NISHI, Ichiro FUJIWARA, Nobutsugu IMANISHI, Hiromichi NAKAHARA†, and Hironobu OKAMOTO††*

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The excitation functions of $^{64}Zn(d, p)^{65}Zn$, $^{64}Zn(d, n)^{65}Ga$, $^{64}Zn(d, 2n)^{64}Ga$, $^{64}Zn(d, \alpha)^{62}Cu$, $^{64}Zn(d, \alpha n)^{61}Cu$, $^{76}Ge(d, p)^{77}Ge$, $^{76}Ge(d, n)^{77}As$, $^{76}Ge(d, 2n)^{76}As$, $^{76}Ge(d, \alpha)^{74}Ga$, and $^{76}Ge(d, \alpha n)^{73}Ga$ were studied with the radiochemical method. The experimental results were analyzed with modified Peaslee's theory. The ρ-values obtained by this analysis were compared with the previous results.

I. INTRODUCTION

Previously K. Otozai *et al.* have investigated excitation functions for the deuteron induced reactions on ^{142}Ce[1], ^{70}Ge, ^{96}Zr, ^{130}Te[2], ^{96}Ru, ^{102}Ru, and ^{104}Ru[3]. With Peaslee's theory modified by introducing the entire absorption parameter they have given a unified explanation not only for the (d, p) reaction but also for the (d, n), (d, 2n), and (d, α) reactions.[1,2] In addition, they have shown that the entire absorption parameter is a monotonical increasing function of isotopic number $(N-Z)$ of the target nuclide up to $(N-Z)=16$ from the systematic consideration of the results.[3]

In the previous works, ^{70}Ge was the smallest in the atomic number and isotopic number. Therefore, in the present work, the excitation functions of deuteron induced reactions on ^{64}Zn whose atomic number and isotopic number are smaller than ^{70}Ge were studied using the radiochemical method. While ^{76}Ge is the neutron richest nuclide of the germanium isotopes, the comparison of the entire absorption parameters between ^{76}Ge and ^{70}Ge should be interesting. The excitation functions of deuteron induced reactions on ^{76}Ge were also studied.

II. EXPERIMENTAL PROCEDURES

1) Irradiation

Metallic zinc foils of natural isotopic abundance were used as targets for the studies of deuteron induced reactions on ^{64}Zn. Germanium oxide powder of enriched isotope (^{76}Ge, 93.55%) obtained from ORNL was sedimented from acetone suspension on an aluminium foil and was used for study of deuteron induced reactions of ^{76}Ge.

* 西　朋太，藤原一郎，今西信嗣，中原弘道，岡本弘信： Institute of Atomic Energy, Kyoto University, Uji, Kyoto.

† Present address: Department of Chemistry, Faculty of Science, Niigata University, Niigata.

†† Present address: Power Reactor and Nuclear Fuel Development Corporation, Tokai Works, Tokai-mura, Ibaraki-ken.

Metallic powder of ^{76}Ge prepared from $^{76}GeO_2$ by hydrogen reduction was used as a target to study $^{77}Ge^m$ whose half life is 56 sec. The target foils were sttacked together with aluminium foils for energy degradation and irradiated by 14.4 MeV deflected deuteron beam from the cycrotron at Kyoto University. The initial energy and its spread were determined every time by the aluminium absorption method. The spread of initial energy was about 0.1 MeV and maximum day to day variation of initial energy was 0.2 MeV.

2) Chemical Separation

The irradiated Zn targets were dissolved in concd. HCl containing each 10 mg carriers of Ga and Cu. The target solution was adjusted to 7 *M* HCl, and was extracted into isopropyl-ether, scrubbed by 7 *M* HCl, and then back-extracted to H_2O. At last, garium oxinate was precipitated from acetic acid solution, and was mounted on a filter-paper.

The residual solution of isopropyl-ether extraction was adjusted to 1 *M* HCl. After adding Na_2SO_3, the solution was warmed to reduce Cu^{2+} to Cu^{+}. CuCNS was precipitated by adding NH_4CNS solution, and was mounted on a filter paper.

The filtrate was saturated with H_2S gas and the precipitate was discarded. After boiling off H_2S, $FeCl_3$, and NH_4OH solution were added. The $Fe(OH)_3$ precipitate was centrifuged off to scavenge Ga activities. ZnS was precipitated with H_2S, and mounted on a filter paper.

The targets of GeO_2 were dissolved in concd. HF containing each 10 mg carriers of As and Ga. The target solution was adjusted to 2 *M* in H_2SO_4 and Ga-cupferate was precipitated by adding alcoholic cupferon solution. Garium cupferate precipitate was dissolved in concd. NH_4OH solution and was scavenged by $Fe(OH)_3$ precipitation. Garium oxinate was precipitated from the acetic acid solution and mounted on a filter–paper. The filtrate was adjusted to 5 *M* in H_2SO_4, and As^{5+} was reduced to As^{3+} by adding NaI. AsS_3 was precipitated with H_2S, but GeS_2 was not precipitated because germanium ion was complexed by enough HF. As_2S_3 was centrifuged, dissolved in aqua-regia and evaporated to dryness to eliminate contamination of Ge activities. Dissolving the residue in 5 *M* H_2SO_4, As_2S_3 was precipitated again and mounted on a filter-paper. The first filtrate of As_2S_3 separation was scavenged twice with As_2S_3 precipitation. Adding bolic acid, GeS_2 was precipitated by bubbling H_2S gas, and was mounted on a filter-paper.

3) Measurement

The γ-rays of samples were measured with 7.5×7.5 cm NaI(Tl) connected to a 400 channel pulse height analyser. The γ-rays of metallic ^{76}Ge targets were measured with a 6 cm^3 Ge(Li) detector immediately after the irradiation without chemical separation. Measured γ-rays were summarized in Table I for $^{64}Zn+d$ reaction and in Table II for $^{76}Ge+d$ reaction, respectively.

The radioactive decay of activities was analyzed using CLSQ program and KDC–2 computer. The chemical yields of Ga and Zn were determined using EDTA titration

Table I. Measured γ-rays for the ^{64}Zn+d Reactions.

Reaction	Half-life of product	Energy of measured γ-rays (MeV)	Emission rate per disintegration
$^{64}Zn(d, p)^{65}Zn$	245. d	1.114	49 %
$^{64}Zn(d, n)^{65}Ga$	15.2 min	1.114 MeV γ-ray of daughter	
$^{64}Zn(d, 2n)^{64}Ga$	2.6 min	3.4251	4.7%
		3.3661	15.7%
$^{64}Zn(d, \alpha)^{62}Cu$	9.9 min	0.511 MeV annihilation β^+	97.8%
$^{64}Zn(d, \alpha n)^{61}Cu$	3.3 hr	0.511 MeV annihilation β^+	62.2%

Table II. Measured γ-rays for the ^{76}Ge+d Reactions.

Reaction	Haif-life of product	Energy of measured γ-rays (MeV)	Emission rate per disintegration
$^{76}Ge(d, p)^{77}Ge^{m}$	56 sec	0.159	IT. 20 %
		0.125	22 %
$^{76}Ge(d, p)^{77}Ge^{g}$	11.3 hr	0.125	100 %
		0.265	100 %
$^{76}Ge(d, n)^{77}As$	38.8 hr	0.240	2.2%
$^{76}Ge(d, 2n)^{76}As$	26.4 hr	0.559	51.3%
		0.657	51.3%
$^{76}Ge(d, \alpha)^{74}Ga$	7.9 min	0.600	98 %
		2.35	49 %
$^{76}Ge(d, \alpha n)^{73}Ga$	4.8 hr	0.296	87 %

and those of As and Ge were determined by colorimetric method.

III. EXPERIMENTAL RESULTS

Cross sections obtained for $^{64}Zn(d, p)^{65}Zn$, $^{64}Zn(d, n)^{65}Ga$, $^{64}Zn(d, 2n)^{64}Ga$, $^{64}Zn(d, \alpha)^{62}Cu$, $^{64}Zn(d, \alpha n)^{61}Cu$, $^{76}Ge(d, p)^{77}Ge$, $^{76}Ge(d, n)^{77}As$, $^{76}Ge(d, 2n)^{76}As$, $^{76}Ge(d, \alpha)^{74}Ga$, and $^{76}Ge(d, \alpha n)^{73}Ga$ are shown in Table III and Table IV, respectively. The data are also plotted in Fig. 1 and Fig. 2. Errors shown in the tables and figures are the standard deviations of the experiments repeated over three times.

Table III. Measured Cross Sections (mb) of Deuteron Induced Reactions on ^{64}Zn.

E_d \ Reaction	(d, p)	(d, n)	(d, 2n)	(d, α)	(d, αn)
3.2		35.9		3.2	
3.5	93.6	30.3		4.8	
3.6		35.9		3.3	
5.1	399.3	122.5		22.4	
6.8	572.7	147.6		41.4	
6.9	477.8	179.4		32.9	
8.4	526.6	154.7		52.0	1.8
10.7	367.8	117.2		52.0	16.7
10.8	398.4	114.8		50.3	12.8
12.5	322.3±4.8	85.0±3.6	9.9±0.7	34.3±1.2	39.6±1.2
13.9	284.9±5.9	70.5±1.4	50.1±1.9	26.8±3.1	62.6±4.3

Table IV. Measured Cross Sections (mb) of Deuteron Induced Reactions on ^{76}Ge.

E_d \ Reaction	(d, p)	(d, n)	(d, 2n)	(d, α)	(d, αn)
3.2		21.5			
3.5	61.7	75	1.9		
3.8					
5.0	116.8	172	110		
6.9	224.1		348.5		
7.0	245.3	191			
8.6			558		
8.7	252.8	209.0	551	3.8	
10.8				8.1	1.0
11.1	204.0	171.3			
12.8				6.1	3.1
12.9	189.4	156.3	738	5.6	
14.4	140.2±13.7	86.3±1.7	814.3±8.0	5.9±0.8	4.6±1.1

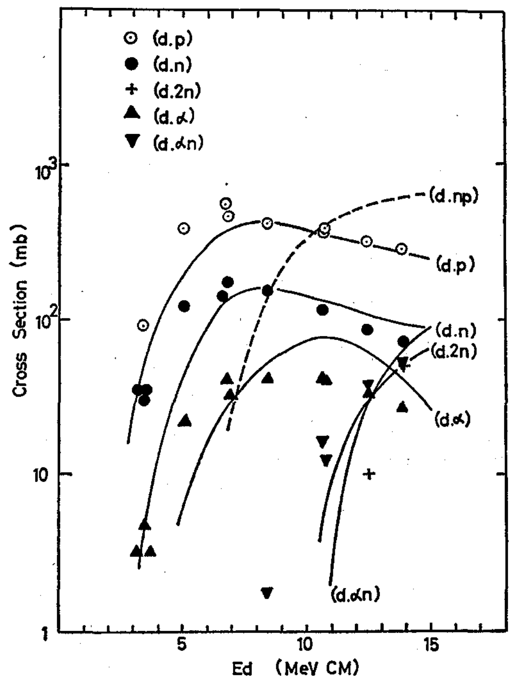

Fig. 1. Excitation functions for the ^{64}Zn+d reactions.

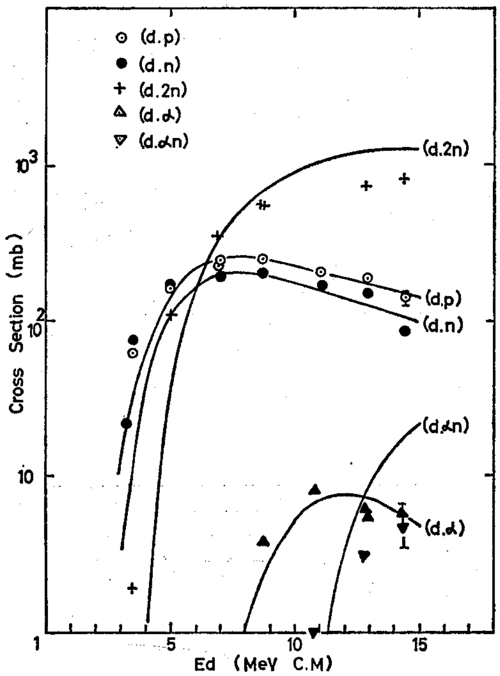

Fig. 2. Excitation functions for the ^{76}Ge+d reactions.

Cross sections for ^{76}Ge(d, p)^{77}Ge^m and ^{76}Ge(d, p)^{77}Ge^g reactions were determined independently and summed up to the total cross section of ^{76}Ge(d, p)^{77}Ge.

IV. DISCUSSION

Experimental excitation functions were analyzed with the modified Peaslee's theory mentioned before. The value 1.6 fm for r_0 and 1.0 for ξ_n were used in the previous works. In the present work, the value for ξ_p and ρ are assumed to be 0.4 and 0.5 fm, respectively, in the case of ^{64}Zn+d reaction, and 1.0 and 1.6 fm in the case of ^{76}Ge+d reaction, to reproduce the experimental excitation functions. The final results of the analysis are shown by the lines in Fig. 3 and Fig. 4. While the value of ξ_n was assumed to be 1.0 for all nuclides, that of ξ_p was assumed to be 1.0 for neutron rich nuclides but smaller than unity for neutron deficient nuclides both in the previous works and in the present one. However, experiments of deuteron induced reaction on neutron deficient nuclides are rather few. Only ξ_p-value of 0.5 for ^{70}Ge+d reaction and 0.4 for ^{64}Zn+d reaction are known, and the reason of this small ξ_p-value for neutron deficient nuclides is not clear. The correlation of ρ-value with isotopic number $N-Z$ of target nuclides are shown in Fig. 3. The ρ-values for ^{64}Zn and ^{76}Ge seem to be a little larger than the smooth curve shown in the previous work, but they are in the limits of error of ρ-values to reproduce experimental excitation functions. The energy dependence of the cross section of n-stripping, p-stripping and entire absorption processes for ^{64}Zn+d and ^{76}Ge+d obtained from the analysis are shown along with the results of previous studies in Fig. 4. The abscissa represents the incident deuteron

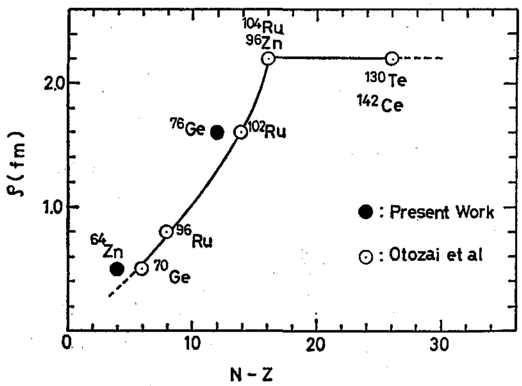

Fig. 3. Correlation between ρ-value and isotopic number.

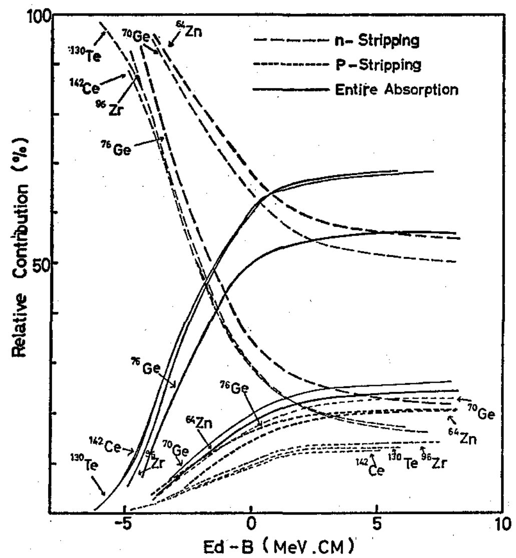

Fig. 4. Relative contributions of the three processes to the total reaction cross section; Symbol B denotes Coulomb barriers for the respective reactions.

energy minus Coulomb barrier for the respective target nuclides.

For the $^{64}Zn+d$ reactions n-stripping process is predominant only in the lower energy region than Coulomb barrier, and entire absorption process is predominant in the higher energy region.

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